L'. DORČÁK, J. TERPÁK, I. PODLUBNÝ, L. PIVKA

ISSN 0543-5846
METABK 49(2) 75-78 (2010)
UDC – UDK 669.162.2:519.673=111

METHODS FOR MONITORING HEAT FLOW INTENSITY IN THE BLAST FURNACE WALL

Received – Prispjelo: 2008-10-24
Accepted – Prihvaćeno: 2009-07-10
Original Scientific Paper – Izvorni znanstveni rad

In this paper we present the main features of an online system for real-time monitoring of the bottom part of the blast furnace. Firstly, monitoring concerns the furnace walls and furnace bottom temperatures measurement and their visualization. Secondly, monitored are the heat flows of the furnace walls and furnace bottom. In the case of two measured temperatures, the heat flow is calculated using multi-layer implicit difference scheme and in the case of only one measured temperature, the heat flow is calculated using a method based on application of fractional-order derivatives. Thirdly, monitored is the theoretical temperature of the blast furnace combustion process in the area of tuyeres.

Key words: blast furnace, thermal load, real-time monitoring, heat fluxes, isotherms

Metode praćenja intenziteta toplinskog toka u stjenci visoke peći. U radu se prikazuju osnovna svojstva on-line sustava za praćeenje u realnom vremenu donjeg dijela visoke peći. Prvo, praćenje obuhvaća mjerenje temperatura stijenki i dna visoke peći te njihovu vizualizaciju. Drugo, prate se toplinski tokovi na stijenkama i dnu peći. U slučaju dvaput izmjerene temperature, toplinski tok se računa korištenjem višeslojne implicitne sheme diferencije, a u slučaju samo jednom izmjerene temperature, toplinski tok se računa korištenjem metode koja se temelji na primjeni frakcionalnih derivacija. Treće, prati se teoretska temperatra procesa izgaranja u području otvora za zrak.

Ključne riječi: visoka peć, toplinsko opterećenje, praćenje u realnom vremenu, gustoće toplinskog toka, izoterme

INTRODUCTION

One of the crucial processes in iron production is the use of the blast furnace. The blast furnace is a countercurrent chemical reactor that melts down ore and burns coke. Ascend gases reduce descending iron oxide particles through series of chemical reductions and as a result outputs pig iron [1 - 5]. Due to the coexistence of several phases and the complex flow conditions, a blast furnace is a very complex aggregate that is difficult to model and to control. Modernization of the control of the metallurgical processes is very desirable because of their high energy and material consumption. So, the blast furnace process control belongs to the key factors of their economic efficiency [6, 7].

The main purpose of the blast furnace control system is to reach specified pig iron composition, temperature and volume at the tapping. To this we need to find the optimal control data for the upper and lower part of the blast furnace (Figure 1). Difficulty of control of the blast furnace is interrelated moreover with the complexity of data acquisition from the lower zone near hearth. Control system consists mostly of a series of computer models for various phases of blast furnace operation [6, 7].

L'. Dorčák, J. Terpák, I. Podlubný, L. Pivka, BERG - Faculty, Technical University of Košice, Košice, Slovakia

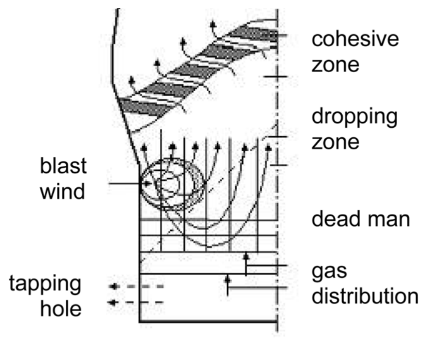

Figure 1. Lower parts of the blast furnace

For the prediction of e.g. hot metal temperature and correct blast furnace control we need input variables about thermal state of the lower part of the blast furnace. Besides directly measured temperature very important variables are theoretical combustion temperature of the blast furnace combustion process, heat fluxes and isotherms in hearth and furnace walls. In this article we present methods for monitoring of these variables.

PROCESS MONITORING AND CONTROL

Monitoring and control of the blast furnace requires first of all an integrated information system with all measured information from the blast furnace, and secondly, some appropriate on-line models. In such environment, a fully integrated on-line system for real-time monitoring of thermal state of the blast furnace lower part has been developed. This on-line system is based upon these basic components:

- Measurement, processing, archiving and visualization of the important parameters
- Models for heat generation and transfer
- Sensitivity analysis of the theoretical combustion temperature with injected fuel
- Models for heat fluxes calculation
- Isotherms and hearth wear calculation.

Fundamental for all these components are the mathematical models that consider all essential processes, and by using measured data - temperatures, hot wind parameters, etc. - calculate heat fluxes, isotherms and the theoretical temperature of the blast furnace combustion process in the area of tuyeres.

Data measurement and processing

For defined purposes the most important measured data are hot wind parameters, temperatures of furnace stack, belly, bosh, hearth, hearth bottom and foot plate. Measured data are sequentially:

- Tested, statistically processed and archived
- Visualized in tables or figures with temperatures values and sensors positions
- Used for heat fluxes and desired isotherms calculation and visualization.

Models for heat generation and transfer

As has been noted, intense heat is required as an input in the production of iron. The main part of heat is generated in the raceway zone in front of the blast tuyeres, where hot wind with powder coal, oil, oxygen, steam, etc. is piped and the coke and injected fuels are burned.

Heat generation is characterized by theoretical combustion temperature that is computed from heat balance [4, 8] and as well by composition of reduction gases. This balance includes combustion of carbon to carbon monoxide, physical heat of hot blast, coke and injected fuels, water vapour dissociation heat, heat of injected fuels:

$$T_{\mathrm{teor}} = \frac{Q_{\mathrm{c}} + Q_{\mathrm{k}} + Q_{\mathrm{v}} - Q_{\mathrm{dis}} + Q_{\mathrm{inj}}}{c_{\mathrm{H_2}} V_{\mathrm{H_2}} + c_{\mathrm{CO}} V_{\mathrm{CO}} + c_{\mathrm{N_2}} V_{\mathrm{N_2}}}, \qquad (1)$$

where Q_c is the carbon combustion heat from coke and injected fuels / kJ/kg$_{coke}$, Q_k is the physical heat of coke / kJ/kg$_{coke}$, Q_v is the physical heat of blast air / kJ/kg$_{coke}$, Q_{dis} is the dissociation heat of water vapour and injected fuels / kJ/kg$_{coke}$, Q_{inj} is the physical heat of injected fuels / kJ/kg$_{coke}$, V_{H_2}, V_{CO}, V_{N_2} is the volume of H_2, CO and N_2 in the combustion gas / m^3/kg$_{coke}$, c_{H_2}, c_{CO}, c_{N_2} is the specific heat capacity of H_2, CO and N_2 / kJ/(m^3 ·K).

The heat transfer from the gases to walls or from the walls to cooling air or water was described with the model of radiation [9] and convective heat transfer:

$$Q_{r,i} = \frac{\sum_{j=1}^{NC} QE_j}{\sum_{j=1}^{NC} A_j} A_i - QE_i,\; Q_{c,i} = K_c S(T_g - T_i), \quad (2)$$

where $QE_j = \sigma A_j T_j^4$ / W is the radiation flux of zone j, σ is the Stefan-Boltzmann constant, A_i / m^2 is equal to εS for surface zone with area S and emisivity ε and $4V\alpha$, for volume zones with volume V and absorptivity coefficient α, K_c is the convective heat transfer coefficient / W/(m^2 ·K) and T_j / K is the temperature of the j-th zone. NC is total number of zones.

Sensitivity analysis

Sensitivity analysis with respect to the most important model parameters like charge composition and distribution of gas volume and temperature etc. is carried out (Figure 2).

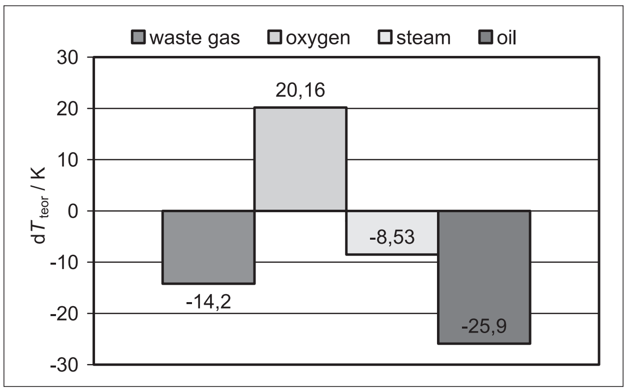

Figure 2. Sensitivity analysis

Each input variable is examined in relation to the output variable, the theoretical combustion temperature. Sensitivity analysis gives an insight into how a change in the parameter would effect the model output. It provides the information on the significance and accuracy with which input parameters have to be estimated and controlled. The positive sign of the coefficient indicates that the input parameter "moves" in the same direction as the output parameter. The negative sign indicates movement in the opposite direction.

Figure 2 represents sensitivity analysis of theoretical combustion temperature with injected fuel. Surprising result was e.g. the big negative influence of the supplied waste oil, which was not controlled.

Heat fluxes and isotherms calculation

In the area of hearth, hearth bottom and foot plate the equations for heat fluxes and isotherms calculation have simplified form:

$$t_g - t_1 = q\frac{1}{\alpha_g},\ t_1 - t_2 = q\frac{x_1}{\lambda_1(t_1)},\ldots$$
$$t_{10} - t_{CO} = q\frac{1}{\alpha_{CO}},\ \text{or}\ \Delta t_{CO} = \frac{q}{V\cdot c}. \tag{3}$$

Measured temperatures, calculated heat fluxes and isotherms are visualized in on-line figures and also used for hearth and hearth bottom wear monitoring.

On the other hand, a one-dimensional mathematical model based on the solution of a non-steady energy equation was employed in the furnace walls with measured temperatures at two different points in each desired location of the wall [10]. In these positions the heat conduction equation (4) was solved in the multi-layer refractory linings:

$$\frac{\partial}{\partial\tau}(c(T)\rho(T)T(t,x)) = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T(t,x)}{\partial x}\right), \tag{4}$$

where T is the temperature / K (measured temperatures are boundary conditions), λ is the heat conductivity / W/(m·K), ρ is the specific weight / kg/m^3, c is the specific heat capacity / kJ/(m^3·K).

From the calculated temperature distribution were calculated the heat fluxes:

$$q_{\text{surf,i}} = \lambda\frac{\partial T}{\partial x},\ /\ \text{W/m}^2 \tag{5}$$

The flux values and isotherms obtained by previous methods (Table 1) matched closely with the values reported elsewhere.

Table 1. **Thermal fluxes / MJ/(m^2·h)**

Heat flux at position of	Averages	Quadrant I.	Quadrant II.	Quadrant III.	Quadrant IV.
Stack	242,7	207,8	284,9	338,1	140,1
Belly	103,5	100,5	102,9	103,7	107,0
Hearth	159,8	112,5	228,1	88,8	209,6
Bosh	8,2	7,9	8,5	8,5	7,7
Hearth bottom	6,3	6,3	6,3	6,3	6,3

This method requires the use of two temperature monitors at two points with different depth within the furnace wall. It is necessary to take into account their relatively high malfunction rate as a consequence of higher operation temperatures and the possibilities of mechanical damage.

In the area with only one measured tempe- rature the heat fluxes were calculated with method based on the half-order derivation ${}_0D_t^{1/2}$ [10, 11, 12] of the measured temperature:

$$q_{\text{surf,i}} = \sqrt{\hat{c}\hat{\rho}\hat{\lambda}}\cdot{}_0D_t^{1/2}(g(t)), \quad g(t) = (T_{\text{surf}}(t) - T_0). \tag{6}$$

The calculated heat fluxes are archived and so hours, workshift, and daily average values. The history of thermal load can be seen in the form of tables (Table 1) or graphs.

Fractional-order derivatives calculation

The problem of determining the thermal flux using equation (6) is now reduced to the calculation of the derivative of half order (non-integer order or fractional-order (FO)) what is not so usual. In the last decades there has been, besides the theoretical research of FO derivatives and integrals [11, 12], a growing number of applications of FO calculus in many different areas such as e.g. chaos, long electrical lines, electrochemical processes, dielectric polarization, colored noise, viscoelastic materials and of course in control theory as well [13, 14, 15] and so on.

For solving the half order derivative [10, 11, 15] in equation (6) we used for the discretizing [16] the Grunwald-Letnikov definition of the operator [12]:

$${}_aD_t^r g(t) = \lim_{\tau\to 0}\frac{1}{\tau^r}\sum_{j=0}^{\left[\frac{t-a}{\tau}\right]} b_j^{(r)} g(t - j\tau), \tag{7}$$

where $[x]$ means the integer part of x, are binomial coefficients [10, 11, 12, 15], τ is time step. In order to reduce the computation cost and to eliminate the round-off error accumulation we apply the principle of "short memory", formulated in [12]. To ensure good precision in the following computation we have used the minimum "memory length" 300.

Both methods (4, 5) and (6) were implemented and compared. The first, conventional method, was used also for testing the second, unconventional method. For these purposes we have used two types of testing signals. The first was the harmonic change of the temperature at one point of the testing equipment (cooper rod). The results are depictured in Figure 3.

We can see, that the heat fluxes of both methods have the same response, the same phase shift in respect of temperature behavior. The differences are in the amplitudes, the amplitude of the second method is bigger compared to the first method. The reason is that the test-

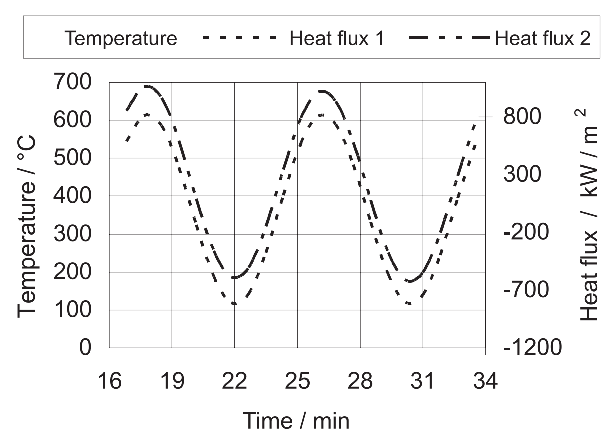

Figure 3. Behavior for harmonic testing signal

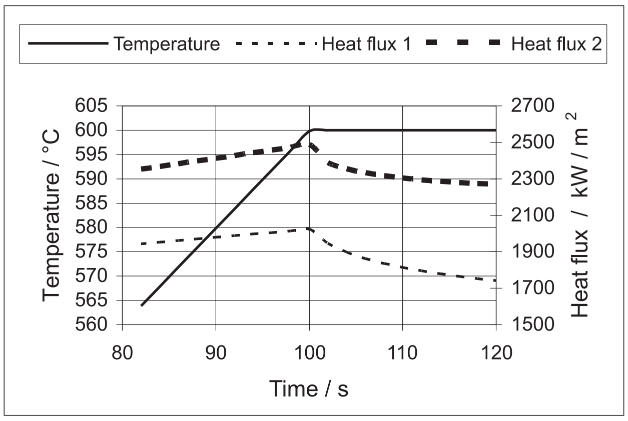

Figure 4. Behavior for ramp testing signal

ing signal has direct-current component. The difference we can calculate as its half order derivative, that is not zero in the case of FO derivative. If the signal has zero direct-current component, the results of both methods are identical.

As the second testing signal we have used the ramp function. The results of both methods are depictured in Figure 4. The heat fluxes of both methods have again very similar behavior.

It can be seen from these results that the method based on the use of FO derivatives and of the temperature measurement in one point only can be used especially for the materials with lower heat conductivity, since it correctly reflects the process both qualitatively and quantitatively. The reason for this success is that for these materials the approximation of the walls width by a semiinfinite body ensures a very satisfactory adequacy of the model. In the case of materials with larger heat conductivity, the proposed method is rather less successful, however, it can still be used for a rough estimate of the changes of the intensity of heat fluxes, if for some reason (malfunction of one of the thermocouples) only the temperature in one point is known.

For all mentioned methods software has been developed based on the described models.

CONCLUSIONS

The described models and the on-line system are still in practice with significant impact for blast furnace monitoring and control. The on-line system enables to monitor directly measured temperatures, calculated theoretical combustion temperature, heat fluxes in lower and upper part of the blast furnace and isotherms that can be used for hearth and hearth bottom wear monitoring. Furthermore, plant operators can take any necessary corrective action to ensure the successful operating of the blast furnace. Minimized is the risk of thermally unsuitable situations with possibility of improving the pig iron quality and reducing the energy consumption.

Acknowledgements - This work was partially supported by grants VEGA 1/0404/08, 1/0365/08 and 1/4058/07 from the Slovak Grant Agency for Science.

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Note: The responsible translator for English language is Ladislav Pivka, Košice, Slovakia.